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Bias in estimating bycatch-to-shrimp ratios

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Abstract

Two methods for estimating bycatch-to-shrimp ratios were tested using Monte Carlo simulations. The Ratio Averager first calculates the ratio of bycatch to shrimp for each element of the sample and then averages all the entire sample. This method overestimated the ratio with a maximum bias as high as 4.5 times. In contrast, the Ratio Estimator or Ratio Estimation as termed in some literature first averages the sample catch rate of bycatch and shrimp and then calculates the ratio of the two averages. The Ratio Estimator performed quite well under all scenarios evaluated in this study, with a bias range from –1.7% to 2.8%. The reliability of the Ratio Estimator was also higher than the Ratio Averager, particularly when both bycatch and shrimp had high variability. Two sets of fishery survey data were used to demonstrate the difference in ratio estimates between the two methods.

Résumé

Biais dans l'estimation des rapports prises accessoires - crevettes. Deux méthodes pour l'estimation des rapports prises accessoires - crevettes ont été testées en utilisant des simulations de type Monte Carlo. Le "quotient moyen" est calculé à partir du quotient des captures accessoires-crevettes de chaque élément de l'échantillon, et ensuite en calculant la moyenne de tous les quotients de l'échantillon. Cette méthode surestime le quotient avec un biais maximum allant jusqu'à 4,5 fois. En revanche, "l'estimation par le quotient" est calculé à partir des moyennes des taux de captures des prises accessoires et celles des crevettes, puis le quotient des deux moyennes est ensuite calculé. Cette dernière estimation présente de bons résultats avec tous les scénarios évalués dans cette étude, avec un biais de –1,7 à 2,8%. La fiabilité de cette méthode est également plus élevée que celle du quotient moyen, particulièrement quand à la fois crevettes et prises accessoires ont une forte variabilité. Deux séries de données de campagnes de pêche sont utilisées pour démontrer la différence dans les estimations entre ces deux méthodes.

Keywords: Bycatch-to-shrimp ratio; Monte Carlo simulation

1. Introduction

The issue of bycatch is important to both fisheries researchers and managers as the influence of fishing effort directed on single species has an impact on other components of the marine ecosystem. A recent study of bycatch estimated that 17.9 to 39.5 million tonnes of fish are discarded annually from commercial fisheries (Alverson et al., 1994; FAO, 1999). Among the various fisheries, shrimp trawling has the greatest level of bycatch because of the poor selectivity of the fine-meshed shrimp nets (Slavin, 1982). Because shrimp are a small fraction of the total catch in most shrimp fisheries (Andrew and Pepperell, 1992), most studies of bycatch have concentrated on estimating bycatch-to-shrimp ratios (Alverson and Hughes, 1996), and relied on those ratio estimates and shrimp catches to estimate total bycatch (e.g., Keiser, 1977a).

Two methods are most frequently used in estimating bycatch-to-shrimp ratios: Ratio Estimator (e.g. Mathews and Samuel, 1983; Silas et al., 1984; Unar and Naamin, 1984; Harris and Poiner, 1990) and Ratio Averager (e.g. Cummins and Jones, 1973; Keiser, 1977b; Pelgrom and Sulemane, 1982; Watts and Pellegrin, 1982; Berghahn,

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1990; Andrew and Pepperell, 1992; Walter 1997; Pettovello, 1999). These two methods produce estimates that are quite different. This not only leads to very different total bycatch estimates, but also makes the ratio estimates incomparable among different studies. Ye et al. (2000) recognized the differences in resulting ratio estimates from the two methods, but so far no study has examined the reliability and precision of each method. This study uses Monte Carlo simulations to test their robustness under known sampling conditions and applies both methods to practical fishery data to examine the difference in ratio estimates.

2. Materials and Methods

2.1. Methods used in ratio estimation

The level of bycatch and the abundance of shrimp within the geographic domain of a fishery are likely to vary from area to area and with time (Andrew and Pepperell, 1992). To estimate the ratio of two populations, samples should be collected from the whole domain of the populations over the time period of concern (e.g. duration of the fishing season). The data for estimating bycatch-to-shrimp ratios are often obtained from observer programs or independent surveys such as research vessel fishing surveys. In both cases, catches of bycatch and shrimp are recorded for each trawl. The ratio of bycatch to shrimp is then estimated from the catch records with either the Ratio Estimator or Ratio Averager.

The Ratio Estimator (Scheaffer et al., 1990; Levy and Lemeshow, 1991) first calculates the average catch rates of sampling trawls for both bycatch and shrimp, and then divides the average bycatch rate with the average shrimp catch rate. The ratio is thus defined as follows:

$$\hat{R} = \frac{\hat{\mu}_b}{\hat{\mu}_s} = \frac{\sum_{i=1}^{n} b_i}{\sum_{i=1}^{n} s_i} \quad (1)$$

where $\hat{\mu}_b$ is mean bycatch per trawl; $\hat{\mu}_s$ is mean shrimp catch per trawl; n is sample size; b_i is bycatch for trawl i; and s_i is shrimp catch for trawl i.

Its variance is:

$$V(\hat{R}) = \frac{N-n}{nN} \frac{1}{\mu_s^2} \frac{\sum_{i=1}^{n} (b_i - \hat{R}s_i)^2}{n-1} \quad (2)$$

where N is population size and μ_s is population mean of s, which is unknown in most cases and replaced with a sample mean:

$$\hat{\mu}_s = \frac{1}{n} \sum_{i=1}^{n} s_i$$

With the variance, confidence intervals of the ratio $\hat{R}$ can be calculated according to normal statistics. Most shrimp fisheries have catch statistics, and total bycatch is then the product of the ratio and total shrimp catch.

The Ratio Averager, however, first estimates the ratio of bycatch to shrimp for each trawl and then takes the mean of all the sample ratios as the total ratio of bycatch to shrimp in the area concerned. That is:

$$\hat{\mu}_r = \frac{1}{n} \sum_{i=1}^{n} r_i = \frac{1}{n} \sum_{i=1}^{n} \frac{b_i}{s_i} \quad (3)$$

where r_i is ratio of bycatch to shrimp for trawl i; $\hat{\mu}_r$ is mean of all sample ratios, and the remaining symbols have the same meanings as in Equation 1. Each trawl tow is treated equally, regardless of the differences in tow duration. The sample variance is then:

$$V(\hat{\mu}_r) = \frac{N-n}{nN} \frac{1}{n-1} \sum_{i=1}^{n} (r_i - \hat{\mu}_r)^2 \quad (4)$$

Accordingly, confidence intervals for $\hat{\mu}_r$, total bycatch estimate and its confidence boundaries can then be calculated.

The Ratio Estimator and Ratio Averager differ only in the order of calculation. The first averages the sample catch rates of bycatch and shrimp and then calculates the ratio of the two average rates, but the latter calculates ratios for each trawl and then averages them. In bycatch studies from shrimp fisheries, the Ratio Averager has been used more than the Ratio Estimator.

2.2. Monte Carlo simulation

Monte Carlo simulations were performed by randomly drawing samples from simulated shrimp and bycatch populations with known density distributions to assess the accuracy of estimates of the Ratio Estimator and Ratio Averager. Here, I consider two possible scenarios of the relationship of the density distributions of the two populations. The first scenario is that the two populations are distributed independently within the survey area, such as observed by Harris and Poiner (1990) and Cummins and Jones (1973). The Second scenario is that the two populations are not independently distributed, as observed in monthly surveys from Kuwaiti waters (Ye unpublished data).

In independent distributions, both bycatch and shrimp were assumed to follow a lognormal distribution. Shrimp distribution was generated by:

$$S = e^x \quad (5)$$

and bycatch was:

$$B = ae^x \quad (6)$$

Table 1
Comparison of variance, bias and MSE between the two methods in the case of independent distributions.

		Ratio=1		Ratio=5		Ratio=10	
CV_b-CV_s		RE	RA	RE	RA	RE	RA
0.5-0.5	Variance	<0.01	0.01	0.07	0.14	0.29	0.56
(r≈0.07)*	MSE	<0.01	0.74	0.69	1.94	0.29	7.71
	Bias (%)	0.3	26.8	0.13	26.6	0.1	26.7
1.0-1.0	Variance	0.01	0.08	0.32	2.06	1.05	9.71
(r≈0.07)	MSE	0.01	1.61	0.32	37.20	1.05	161.69
	Bias (%)	1.13	120.8	-0.04	118.6	0.9	122.8
2.0-2.0	Variance	0.04	3.18	0.98	51.97	4.13	230.42
(r≈0.05)	MSE	0.04	25.14	0.99	534.82	4.15	2258.04
	Bias (%)	0.7	452.8	2.2	435.9	1.4	446.6
0.5-2.0	Variance	0.02	0.03	0.56	21.32	2.36	87.09
(r≈0.06)	MSE	0.02	20.08	0.56	464.04	2.40	1864.89
	Bias (%)	1.8	416.1	1.2	418.6	1.9	419.5
2.0-0.5	Variance	0.02	0.98	0.56	0.82	2.37	3.44
(r≈0.06)	MSE	0.50	27.98	0.56	2.75	2.40	10.81
	Bias (%)	0.5	28.0	-0.7	27.6	-1.7	27.0

* The correlation coefficient changes slightly with the ratio level even if the CVs are fixed.

where

$$x \in N(\mu, \sigma^2) \quad (7)$$

meaning that x is identically and independently distributed according to a normal distribution with a mean of μ and variance of σ^2, and a is a constant. The x variables in Equations 5 and 6 were drawn from normal distributions of the same μ, but different values of σ^2 to produce different coefficients of variation (CVs) as shown in Table 1. The lognormal distribution was chosen for two reasons. First, an examination of the survey data shows that they have long tails, and the lognormal approximates this better than a normal distribution. Second, the lognormal assumption is the most frequent choice in biological studies (Mohn 1993). The ratio of the two populations, S and B, was altered by changing a while the variability of variable x was controlled by σ^2. Thus, the effects of both ratio level and variability on the two ratio estimators could be assessed.

With dependent distributions, where bycatch and shrimp are not distributed independently, but are related to each other, an extra term was added to a lognormally distributed population:

$$S = e^{x + \varepsilon_s} \quad (8)$$

where

$$\varepsilon_s \in N(0, \sigma_s^2)$$

S is shrimp, and x is defined as in Equation 7. The bycatch distribution was generated by:

$$B = ae^{x + \varepsilon_b} \quad (9)$$

where

$$\varepsilon_b \in N(0, \sigma_b^2)$$

B is bycatch, and a is a constant. The x values in Equations 8 and 9 were drawn from normal distributions of the same μ and σ^2 for all the dependent data sets. Changing a in Equation 9 resulted in different bycatch-to-shrimp ratios. Altering CVs through changes in σ_s^2 and σ_b^2 controlled the degree of correlation between the two populations.

For each test, 1000 pairs of data were generated for shrimp and bycatch populations. Randomly sampling the generated populations 200 times with a sample size of 200 in each sampling produced bycatch and shrimp sample data sets. Both the Ratio Estimator and Ratio Averager were then applied to each set of sample data to estimate the total ratio of the two populations. The mean of the 200 estimates of the population ratio was finally contrasted with the known ratio value, and its bias, variance, and mean square error (MSE) were calculated to compare the two methods.

Population densities were contrasted in terms of their CVs. I chose three CV levels, 0.5, 1.0 and 2.0, to reflect the range of values observed in monthly surveys of shrimp and bycatch populations from Kuwaiti waters (Ye unpublished data). Bycatch ratios of 1:1, 5:1 and 10:1 were chosen to reflect the range of values reported from temperate and tropical waters (Slavin, 1982; Andrew and Pepperell, 1992) (Table 1). When populations are not independently distributed, the level of association (i.e. correlation) between the two populations varies with the level of CVs. Larger CVs result in lower correlations when both populations have the same CV. For instance, the correlation coefficient was 0.92 at CV_b=CV_s=0.5 and reduced to 0.13 at CV_b=CV_s=2.0. The mediate CV was changed to 0.7 to make the correlation coefficient have a reasonable interval (Table 2).

Table 2
Comparison of variance, bias and MSE between the two methods in the case of dependent distributions.

		Ratio=1		Ratio=5		Ratio=10	
CV_b-CV_s		RE	RA	RE	RA	RE	RA
0.5-0.5	Variance	<0.01	<0.01	0.01	0.01	0.02	0.02
(r≈0.92)	MSE	<0.01	<0.01	0.01	0.02	0.02	0.08
	Bias (%)	0.1	2.6	0.0	2.5	0.0	2.4
0.7-0.7	Variance	<0.01	0.01	0.06	0.10	0.21	0.32
(r≈0.54)	MSE	<0.01	0.05	0.06	1.19	0.21	4.43
	Bias (%)	0.6	20.9	0.2	20.9	0.0	20.2
2.0-2.0	Variance	0.03	0.81	1.08	25.22	3.47	93.47
(r≈0.13)	MSE	0.04	10.48	1.08	277.84	3.55	299.44
	Bias (%)	2.3	304.0	0.5	314.4	2.8	299.2
0.5-2.0	Variance	0.02	0.20	0.49	4.37	1.45	18.66
(r≈0.27)	MSE	0.02	7.97	0.50	202.12	1.49	798.18
	Bias (%)	0.7	271.9	2.1	278.7	2.1	276.6
2.0-0.5	Variance	0.02	0.02	0.45	0.37	1.89	1.34
(r≈0.31)	MSE	0.02	0.01	0.45	0.37	1.89	1.34
	Bias (%)	0.5	0.9	-0.9	0.8	-0.4	0.4

2.3. *Practical examples*

Two sets of shrimp fishery survey data were used in this study. One was from the survey along the southeast coast of South America presented by Cummins and Jones (1973), and the other was obtained from Kuwait's shrimp fishery survey in August 1987 (Table 3). Initial analysis treated these two data sets as simple random samples and applied both methods to estimate their bycatch-to-shrimp ratios. Spatial patterns observed in the Kuwaiti shrimp survey highlighted the consideration for stratification techniques.

The Kuwaiti survey waters are usually partitioned into three areas based on geography and shrimp distribution: Kuwait Bay, Middle Area, and Southern Area (Ye et al., 2000). The spatial distributions of this specific survey are characterized with lower bycatch rates in Southern Area, and lower shrimp catch rates in Kuwait Bay (Table 3). Consequently, a spatial pattern of bycatch-to-shrimp ratios is clear with Kuwait Bay having the highest ratio, 27.4, and the Southern Area the lowest, 5.6, and the Middle Area in between, 12.3. Stratified sampling or post stratification is normally used for populations of strong spatial distributions for its potentially significant gain in reliability. To study the difference of the two methods in ratio estimates with data of spatial patterns in distribution, I took the survey data in Table 3 as entire populations of shrimp and bycatch. Thus, the ratio of bycatch population to shrimp population is 10.6. I sampled 200 times independently within each stratum. Spatial distributions were first ignored, and the stratified samples from the three strata were combined to form a single random sample (Analysis A, Table 4). Both the Ratio Estimator and Ratio Averager were then applied to estimate bycatch-to-shrimp ratios. The second step, however, followed stratified sampling theory that estimates the population mean as a weighted average of the individual stratum means, with weights proportional to the size of each stratum (Levy and Lemeshow, 1991). Specifically, the population means of bycatch and shrimp rates, $\hat{\mu}_b$ and $\hat{\mu}_s$ in Equation 1, and the ratio of bycatch to shrimp, $\hat{\mu}_r$ in Equation 3, were calculated as weighted averages of individual stratum means (Analysis B, Table 4).

To examine the potential impact of sampling effort distribution on the ratio estimate, I tested two sampling strategies. In the first, I assigned each stratum a sample size proportional to its stratum size, i.e. 2, 4, and 4 for Kuwait

Table 3
Kuwait's shrimp survey data (kg per hour trawling at 3.3knots) in August 1987.

	Kuwait Bay		Middle Area		Southern Area	
	Shrimp	Bycatch	Shrimp	Bycatch	Shrimp	Bycatch
	41.0	740	18.0	180	9.0	320
	0.5	240	30.5	70	104.5	40
	0.5	240	9.0	500	33.0	260
	7.5	140	1.3	240	2.6	140
			4.7	160	13.0	190
			59.0	390	45.5	180
			10.0	1 140	25.5	210
			105.5	150	20.4	90
Mean	12.4	340	29.7	366	31.7	179

Table 4
Means of the ratio estimates of 200 samples from the Kuwaiti survey data in August 1987 (standard error in brackets).

Stratum sample sizes (Kuwait Bay, Middle Area, Southern Area)	Analysis	Ratio Estimator	Ratio Averager
2, 4, 4	A	11.42 (0.15)	77.45 (0.87)
	B	11.42 (0.15)	31.28 (1.06)
2, 6, 6	A	10.28 (0.08)	64.73 (0.63)
	B	10.81 (0.08)	28.14 (1.08)

Bay, Middle Area, and Southern Area, respectively. In the second, sampling effort was more concentrated on areas of high shrimp density by increasing the sample size to 6 in Middle Area and Southern Area (Table 4).

3. Results

For independent distributions, the Ratio Estimator produced lower variance, lower bias and lower MSE than the Ratio Averager in any ratio level with any CV combination (Table 1). The ratio level had a positive effect on variance and MSE, but not on percentage bias. Unlike the population ratio, population CV had a significant effect not only on the variance and MSE, but also on the percentage bias with regard to the real ratio. Most noteworthy, differences for the three statistics between the two methods increased significantly as the CV became larger. For example, given Ratio=1, the variance of the Ratio Estimator was less than 0.01 and that of the Ratio Averager was 0.01 at $CV_b=CV_s=0.5$. It, however, increased to 0.04 and 3.18, respectively, when $CV_b=CV_s=2.0$, presenting a difference of about 80 times (Table 1). The difference in MSE grew even more drastically than that in variance (Table 1). The most apparent discrepancy between the two methods was in the percentage bias. When both populations had the same CV increasing from 0.5 to 2.0 at Ratio=1, the bias of the Ratio Estimator ranged from 0.3% to 1.1%, in sharp contrast with the Ratio Averager bias which increased from 26.8% to 452.8% (Table 1). This indicates that the Ratio Estimator performed much better than the Ratio Averager in estimating the total ratio of two populations, particularly with large CV_s.

When bycatch and shrimp had different CVs, the differences in variance, bias, and MSE between the two methods still remained. However, the difference was larger when shrimp had a larger CV than bycatch. If $CV_s=2.0$ and $CV_b=0.5$, the bias was 1.8% vs. 416.1%. But, when $CV_s=0.5$ and $CV_b=2.0$, the bias was 0.5% vs. 28.0% (Table 1). It appears that the bias level is positively related with shrimp CV.

When populations are not independently distributed, the level of association between the two populations is a major concern. Given that both populations had the same CV the following conclusions can be made: the higher the CV, the lower the correlation, and the larger the differences in variance, bias, or MSE between the two methods (Table 2). When r=0.92, the Ratio Estimator and Ratio Averager had very close variances under all three ratio levels. Although the bias and MSE of the Ratio Averager were higher than those of the Ratio Estimator, the differences were small. As the association between populations was decreased, the difference between estimators increased drastically. Similar trends were also seen for variance and MSE (Table 2). The ratio effects on the difference are similar to those of independent distributions.

When the two population CVs were different, the differences in variance, bias, and MSE between the two methods varied greatly with relative levels of the two CVs, even if the correlation coefficient was similar (Table 2). As in the case of independently distributed populations, the variance in the shrimp population had the greatest effect on the contrast in variance, MSE and bias of the estimators (Table 2). The overall pattern was similar to that of the independent populations although the differences in statistics were substantially reduced.

In general, the Ratio Averager produced inflated ratio estimates, reaching more than four- fold when populations are very patchy (i.e. $CV_b=CV_s=2.0$) (Table 1). In contrast, the Ratio Estimator had a maximum bias of only 2.8% (Table 2). For independent distributions, the Ratio Estimator produced lower variance, bias, and MSE than the Ratio Averager. The relative differences in the three statistics remained almost unchanged over the selected range of population ratios, but became drastically larger with the increasing of population CVs. For dependent distributions, the performance differences between the two methods remained, but to a lesser degree compared to those of independent distributions. Decreasing the level of association of the two populations would increase differences between the two methods.

Andrew and Pepperell (1992) calculated that the ratio of bycatch to shrimp along the southeast coast of South America was 40.2 using a Ratio Averager applied to the survey data from Cummins and Jones (1973). However, if Ratio Estimator were used, the ratio would be estimated at 11.4 with the same set of data. I also applied these two methods to the Kuwaiti shrimp survey data. When the survey was treated as a simple random sample, the Ratio Averager estimated the ratio at 77.0 in sharp contrast with the estimate of 10.6 by the Ratio Estimator. In both cases, the Ratio Averager produced a much higher estimate than the Ratio Estimator.

With the re-sampling of the Kuwaiti shrimp survey data, the Ratio Averager estimated the mean of bycatch-to-shrimp ratios of the 200 samples at 77.45 when no stratification was considered (Analysis A, Table 4) and at 31.28 when stratification techniques were employed (Analysis B, Table 4) in the case where each stratum had a sample size proportional to its size. Although stratification reduced the mean of the ratio estimates remarkably, it was still 3-fold of the true value. The Ratio Estimator, however, produced the same estimate of 11.42 in both analyses (Table 4), which is close to the true ratio. When sampling effort was more concentrated on areas of high shrimp density, the estimates from the Ratio Averager decreased; however, a lesser extent was seen with stratified samplings. Although a similar change was also seen for the Ratio Estimator, its extent was much smaller, and the estimated ratios became closer to the true ratio (Table 4).

4. Discussion

In comparing different estimators, three measures are normally considered: reliability, validity, and accuracy. If it is assumed that there is no measurement error in the survey, the reliability of a Ratio Estimator can be stated in terms of its sampling variance. The smaller the variance of the estimator, the greater is its reliability (Levy and Lemeshow, 1991). Accordingly, the validity of a Ratio Estimator can be evaluated by examining its bias that is defined as the difference between the mean of the sampling distribution of an estimate and the true value. The smaller the bias, the greater is the validity. The accuracy of a ratio is generally evaluated on the basis of its MSE, which is related to its bias and variance (Levy and Lemeshow, 1991).

In terms of all measures of comparison, the Ratio Estimator outperformed the Ratio Averager with lower variance, MSE and bias under all scenarios considered in this study. Of particular importance was the apparently low bias of the Ratio Estimator, which never exceeded 3% whereas that of the Ratio Averager exceeded 400% in cases where the bycatch ratio and the variance in both population density distributions were elevated.

The practical examples showed how large the difference could be between the two ratio estimates derived from Ratio Estimator and Ratio Averager. With populations of spatial distribution, the Ratio Estimator produced estimates close to the true ratio with a survey design of either simple random sampling or stratified random sampling, indicating that spatial distribution would not undermine the reliability of Ratio Estimator. Distribution of sampling effort did have influence on stratum means as in any other random samplings, but its impact on the ratio estimate of two entire populations was limited because it was an average of the stratum means weighted by the size of each stratum. Stratification improved the estimates of the Ratio Averager significantly, but was not able to make the estimates as close to the true ratio as those from the Ratio Estimator.

Monte Carlo simulations and practical applications produced similar contrasts in estimates of bycatch-to-shrimp ratios. Given the results of this study, I concluded that the Ratio Estimator is likely to provide more accurate estimates of the overall bycatch ratio of shrimp fisheries.

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